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THE CYCLE OF EROSION IN A KARST REGION (AFTER CVIJIĆ)

By E. M. Sanders

The Conception of a Karst Cycle

Professor Davis has earned the gratitude of all geographers by standardizing the descriptive terms employed in explaining the various stages in the evolution of land forms in a region of normal climate where the rivers flow upon the surface of the ground. To him and to Professor Siegfried Passarge we also owe a similar development of the idea and terminology of the desert cycle where wind erosion and exportation of land waste in an arid climate combine with perennial stream action to produce a group of distinctive forms. There is no such uniformity, however, to be found in the use of terms to describe the forms evolved in a karst region where the rivers flow underground for the most part. Though much research has been done upon the problem, the results, published in French, English, and German, have not yet been correlated. In 1918 Professor Cvijić, one of the most energetic and original of those who have studied karst topography, published a résumé of former theories on the development of subterranean drainage, supplementing them by the results of his own work and by an ordered description of the successive changes that take place in the progress of the karst cycle.[1]

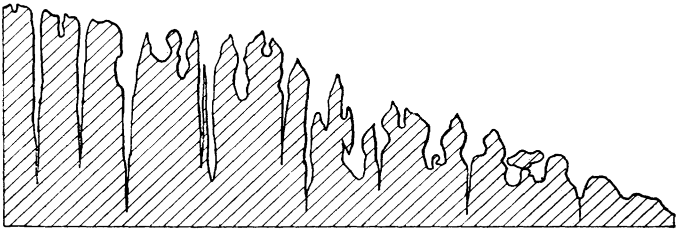

FIG. 1—Lapiez, name given to combined erosion and solution forms developed by water action in the rock fissures of limestone surfaces. From de Martonne, after "Traité de géographie physique", 1913, p. 471.

The article of Professor Cvijić marks a step forward in the science of physiography; but it is far from easy reading for the average geographer since many unfamiliar terms, such as "bogaz" and "ponor," are used without either definition or explanation by synonyms. The terms are often Serbian words which convey no meaning, either by their form or derivation, to those ignorant of the Serbian language. The object of the present article is to present Professor Cvijić's summing up of the whole matter, amplifying it with definitions of the terms used, and giving, where it is possible, the terms[2] used by others for the same forms. Karst is the term corresponding to the French word "causse," a word which Baring-Gould, in "The Deserts of Southern France," has made familiar to English readers. Karst topography is developed in many limestone or dolomite regions, because these rocks weather differently from others. The difference is due principally to the solubility of calcium carbonate in natural waters. The first solution channels owe their pattern to the highly developed system of joints which is nearly always found in such rocks. In a region where karst topography is fully developed the water circulates almost entirely underground.

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[1] Jovan Cvijić: Hydrographie souterraine et évolution morphologique du Karst, *Recueil des Travaux de l'Inst. de Géogr. Alpine*, Vol. 6, 1918, Grenoble, pp. 375–426. By courtesy of Professor Raoul Blanchard the *Geographical Review* has been furnished with the original blocks used in the printing of Professor Cvijić's paper. All of the illustrations are from this source except Figure 1, though Figure 11 has been re-engraved to a smaller size.

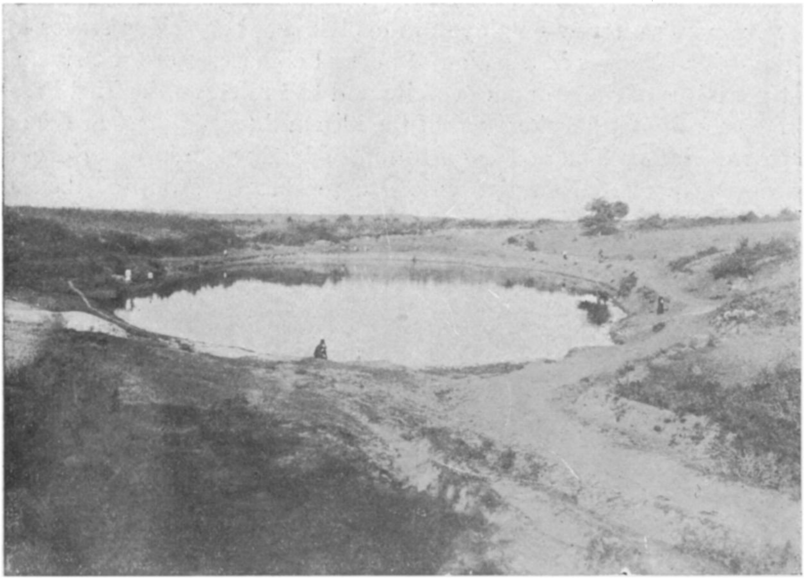

FIG. 2—A lake formed on the floor of a doline or sink hole near Belgrade.

BASIC ASSUMPTIONS

The structure of karst regions is so varied that innumerable complications ensue. Let us, therefore, take one type associated with a structure in which all stages of evolution are possible: a mass of limestone of great purity and solubility, formed of strata inclined at a great angle, with few complications due to crushing, faulting, etc. The thickness of the mass is to be such that, although its base is above sea level, its surface reaches a considerable height. Let us have the mass exposed to a Mediterranean climate with so dry a summer season that only those plants exist which are fed from the roots or which can store up moisture for themselves. This provides that the limestone surface shall not have a thick protective covering of vegetation.

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[2] The equivalent terms and examples are taken from earlier works: from Jovan Cvijić's "Das Karstphänomen" (Geogr. Abhandlungen von A. Penck, Vol. 5, No. 3), Leipzig, 1893; from Emmanuel de Martonne's "Traité de géographie physique;" and from James Geikie's "Earth Sculpture." The dimensions of the different land forms are taken from Cvijić's "La Peninsule Balkanique," Paris, 1918. The identification of "karren" and "lapiez" is taken from Eugène Renevier's "Monographie der Hautes Alpes Vaudoises" (Matériaux pour la carte geol. Suisse), p. 499. Various publications of the U. S. Geological Survey furnish examples of karst topography in the United States.

Since the above was written E. A. Martel's "Nouveau traité des eaux souterraines" (reviewed in this number of the *Geographical Review*) has appeared. The varied terms applied to karst forms are discussed on pp. 130-133.

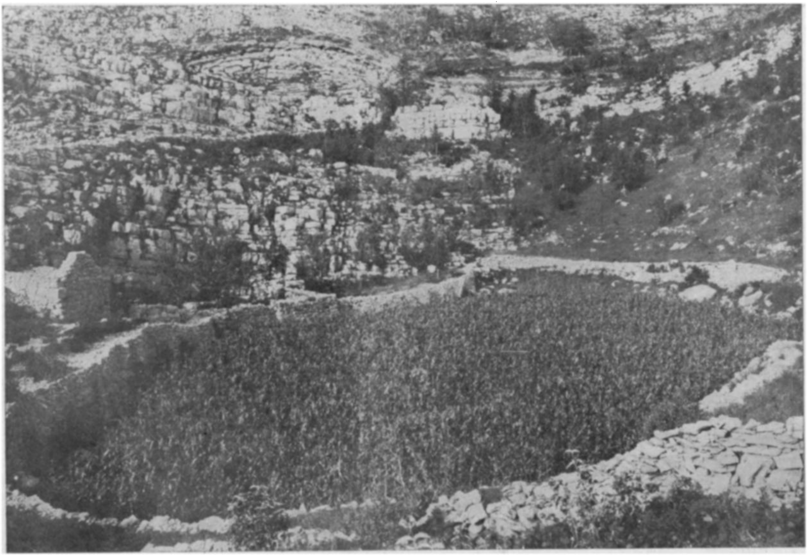

Fig. 3—Cultivated alluvium on the floor of a doline at Cevo, Montenegro. Note tne barren and uncultivated limestone surface roundabout.

Further, let us assume that at a time immediately preceding the inauguration of the cycle of karst erosion there was a covering of impermeable strata over the limestone on which a normal system of streams had developed and that another impermeable layer exists under the base of the limestone mass.

UNDERGROUND WATERS IN THREE HYDROGRAPHIC ZONES

The evolution of the land forms in such a region follows step by step the evolution of the subterranean drainage. It is therefore necessary first to consider the way in which the underground waters develop their channels. Up to the appearance of the article of Professor Cvijić two divergent theories as to the circulation of underground waters held the field.[3]

One of these theories regards the subterranean waters as circulating continuously, all irregularities being explained as due to siphons[4] which force up the water, the stagnant water being regarded as a merely temporary accident. The other theory[5] holds that there is a saturation level in the limestone mass, below which all the crevices of the limestone are filled with water continuously, the only circulation that exists being the descent of the rain that passes through the porous limestone until it reaches the saturation level, after which it is stagnant. Many phenomena, such as the successive displacement of springs and the change of level and final desiccation of the temporary lakes that are found in karst regions, are difficult to explain by either of these theories; and the result of many years of observation has led Professor Cvijić to the conclusion that different conditions exist within the limestone mass at different stages in its evolution—the conditions being sometimes favorable to one of the former theories, and sometimes to the other. He considers that in a fully established karst system there are three hydrographic zones:

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[3] **E. A. Martel:** Notices sur les travaux scientifiques, Paris, 1911.

[4] **F. Katzer:** Karst and Karsthydrographie, *Zur Kunde der Balkanhalbinsel*, 1909. Sarajevo.

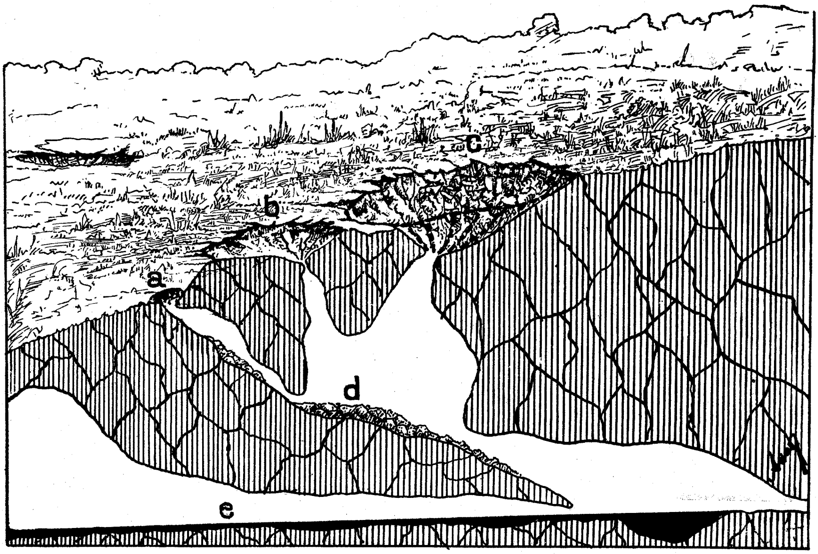

FIG. 4—Underground caves, passages, and drainage, and their connection with dolines or sink holes at the surface. Note the beginnings of waste accumulation underground and the poorly organized state of all drainage slopes. Cave of Petnjica, near Valjevo, Serbia.

(1) The zone immediately beneath the surface is composed of channels and reservoirs which transmit water in time of storm but are usually dry.

(2) The next zone is intermittently dry and wet; its caverns and channels may be flooded for considerable periods but not permanently.

(3) The lowest zone, situated immediately above the junction with the underlying impermeable strata, has permanent streams and reservoirs which are always full of water.

There are many modifications of the ideal scheme due to geologic structure and other causes. Normally, the youthful stage of a karst region is marked by the development of underground drainage so imperfect as to leave a large amount of the water that falls as rain remaining on the surface of the ground, although all the cracks and crevices of the rock are filled with water. In this stage permanent lakes exist. In the next stage the subterranean system is sufficiently developed to carry off all the surface water except in times of exceptional downpour. In this stage intermittent lakes are found. In the perfectly developed system all of the surface water is carried immediately underground, and consequently no lakes exist unless the depressions of the surface are so deep that they dip below the upper level of the saturated zone.

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[5] A. Grund: Die Karsthydrographie. Studien aus Westbosnien (Geogr. Abhandlungen von A. Penck, Vol. 7, No. 3), Leipzig, 1903.

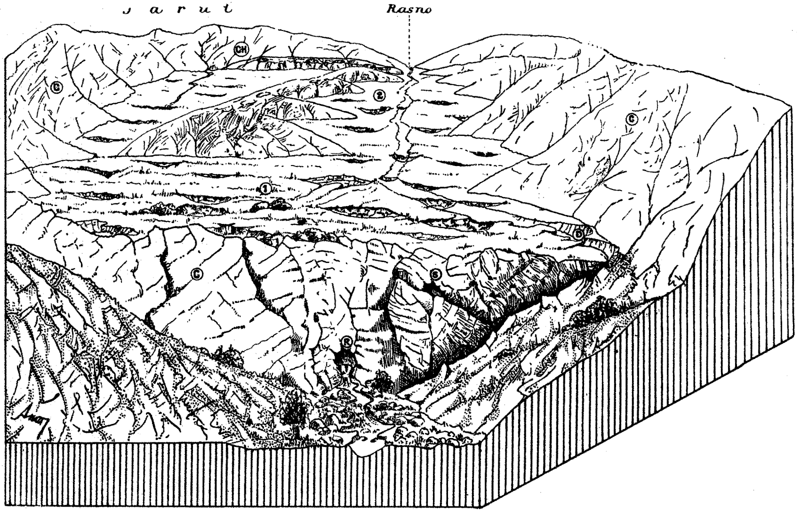

FIG. 5—Type of polje or blind valley of fluvial origin. Polje of Kostan, near Novi-Bazar. At first normal valleys were formed as in the center background and on the right where the main gorge lies now completely dry. After sub-surface changes had diverted the stream underground it issued first at (S) and now at (R) 100 meters lower. The upper part of the Rasno valley, shown in the diagram, is now a young polje, and here also the stream has been diverted underground by the development of ponors or intake openings.

FOUR STAGES IN THE EVOLUTION OF KARST TOPOGRAPHY

Contemporaneous with the development of the underground drainage is the evolution of the land forms of the surface. Four phases are distinguishable, which may be called youth, maturity, late maturity, and old age.

In youth, the surface of the land is still principally drained by the rivers which flow on the former surface of the land before the limestone subject to karsting was laid bare, or when it was at a lower level or had a better climate and denser vegetation and normal surface erosion took place. This earlier development of normal surface drainage is an important feature of Cvijić's explanation, youth being marked by a progressive loss of surface drainage. Rivers flowing above ground disappear, and in some cases the disappearance takes place in a few decades. There are reliable records of recent changes of this sort. Wherever the limestone is exposed to the rain the ground is covered by a network of furrows eaten out of the rock by the dissolving water. Each furrow may be only a few inches wide but is from three to six feet deep. It is as if the hard rock had been deeply plowed, so thoroughly is its surface scored by these furrows (Fig. 1). Such land is avoided by man and beast, for it is exceedingly difficult to traverse. There are many different terms to denote it. In the French Alps "rascles" is the term, while the German equivalent is "Schratten" and "Karren." The name adopted by Professor Cvijić is "lapiez," which is the term used in the French Jura.[6]

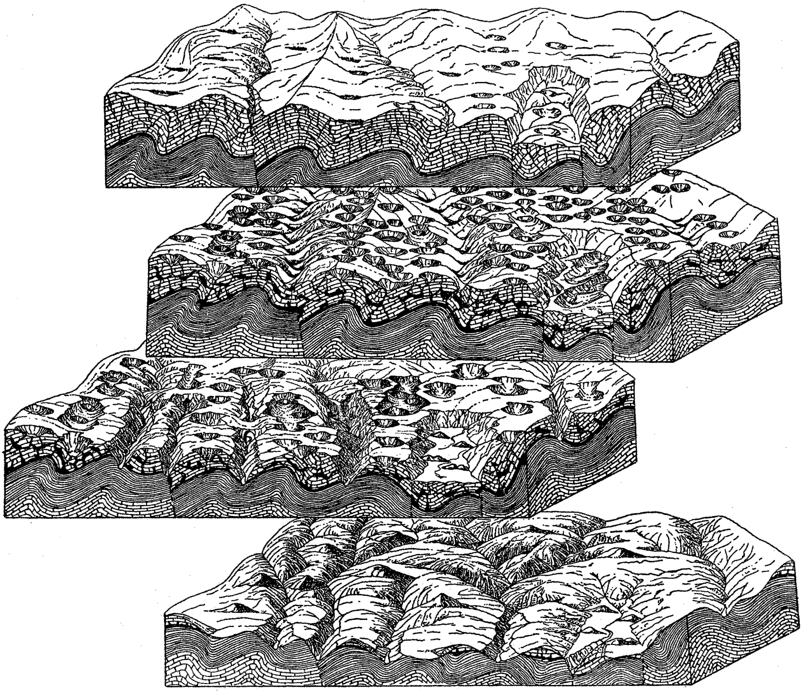

FIG. 6—Four main stages in the evolution of karst topography.

(1) The uppermost block represents a youthful stage of development. There are the beginnings of normal valley cutting in elongated depressions, called poljes, of tectonic origin. Fissures near the surface afford the means of subterranean channeling, and scattered dolines appear.

(2) The next lower block represents maturity or the strongest expression of the karsting process. There are no surface waters save where uvalas have formed by the breaking down of cave roofs. Fissures have been enlarged into caves and reservoirs and the surface valleys of youth have become completely disorganized by dolines and uvalas.

(3) Late maturity is represented by the third block from the top. Valleys are formed, either through the foundering of cave roofs along old valley axes or by the marginal development of underground courses without surface control. In this process many dolines and uvalas of an earlier stage have disappeared. Where ground-water level has been reached, valley widening has begun, and, as in the right foreground, hums appear, that is fragments of the once honeycombed limestone mass.

(4) Old age is represented by the lowermost block. Normal valleys have been cut in the impermeable rocks that form the floor of the limestone mass whose fragments occur scattered here and there in the form of hums.

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[6] Martel: Nouveau traité, pp. 531–550.

Where any line of weakness, such as a fault or bedding plane or joint, allows the water to penetrate more easily, deep and narrow chasms are eaten out. These are termed "bogaz" by Cvijić. The ordinary French term is "gouffre d'absorption."

Such are the beginnings of erosion in the limestone. Little by little, however, the furrows and chasms are deepened, and underground channels are created. Often in the course of a stream such a chasm appears, and soon the streams disappear down holes in the ground in mid-course, leaving their valleys dry either wholly or in part. A valley that is deserted by its stream in this fashion is called a "blind valley" (*vallée morte*). Figure 5 shows two such valleys. The holes down which the streams disappear have many names. Roughly they are of two classes, those that are funnel-shaped and

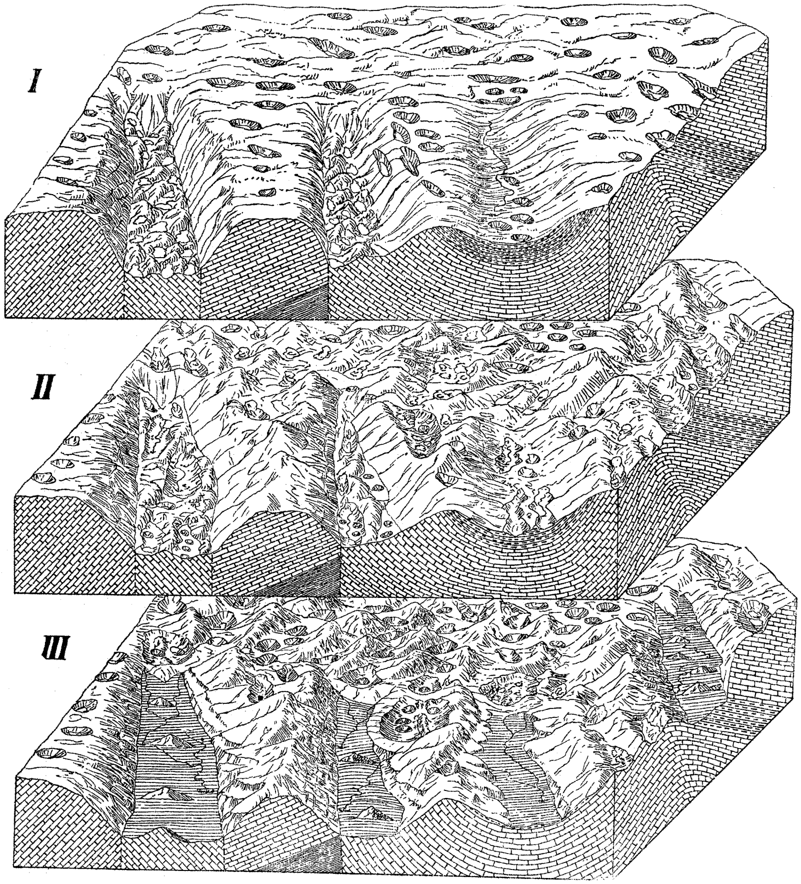

FIG. 7—To illustrate the development of poljes or major elongated depressions.
I. Structural depressions whose origins are shown on the front edge of the block. After moderate normal erosion the effects of karsting have become prominent.
II. The same region at maturity with uvalas and surface drainage in part.
III. Advanced stage of valley development with continuous surface streams and only occasional isolated hums on the valley floors.

those that are cylindrical. The funnel-shaped depressions with a hole in the center have long been called "dolines." The French terms are "sotch" and "cloups," used in the causse region; "creux" and "emposieux," used in the Jura; and all of them correspond to the terms "sink hole," "swallet hole," "cockpit," and "light hole" of English writers. In Yucatan the common word is "cenote."[7]

The shaftlike aperture Cvijić calls "ponor." In French "avens" and "jamas" are commonly employed; but "gouffre," "abime," "puits," "pertes," "betoirs," "sucoirs," "igues," and "tindouls" are also used. The Belgian term is "aiguegeois." The Greek equivalent is "katavrothes," while the German term is "Kesserthaler." The latter term is also used for blind valleys.

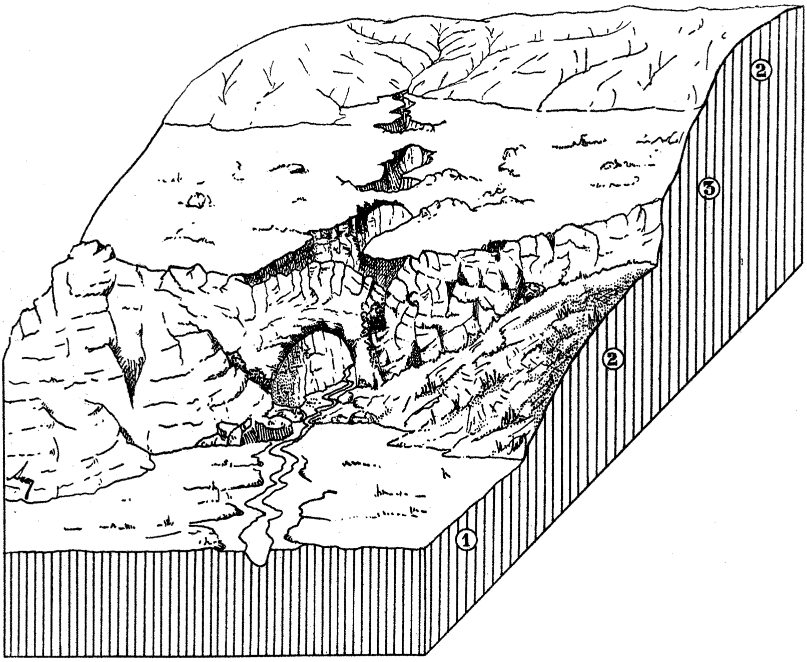

FIG. 8—Cavern transformed into a gorge. The Vratna, a branch of the Danube in eastern Serbia. 1 represents alluvium; 2, sandstone; 3, limestone.

As time goes on, the divisions between neighboring dolines are broken down; and larger depressions, called "uvalas" or "ouvalas," are created. A uvala is usually more than one kilometer in diameter; a doline may be from ten to a thousand meters in diameter. Other large depressions, at least roughly linear in form, are also found in karst regions. They are called "poljes." They may be formed by the junction of several uvalas or they may have originated as blind valleys, or, as most commonly, they may owe their origin to tectonic depression. Many other conditions or accidents may be the original cause of their development. In one way or another and with many possible combinations of conditions, structural and hydrographic, the limestone surface, riddled with ponors and dolines, disappears in places, and great flat-bottomed depressions are formed. Eventually their floors become covered with alluvium as the watercourses work down to impermeable strata or reach normal base level.

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[7] L. J. Cole: The Caverns and People of Northern Yucatan, *Bull. Amer. Geogr. Soc.*, Vol. 42, 1910, pp 321–336.

The youthful stage of karst topography is shown in Figure 6. It will be noticed that the limestone mass is traversed by innumerable fissures, but that no great caverns are as yet formed. The development of the underground system of drainage is far from complete. In the early stages of youth only one hydrographic zone is established; and not until maturity is reached are three zones developed, although toward the end of the period of youth two zones may be distinguished—an upper zone which is flooded intermittently and a lower zone which is always completely saturated.

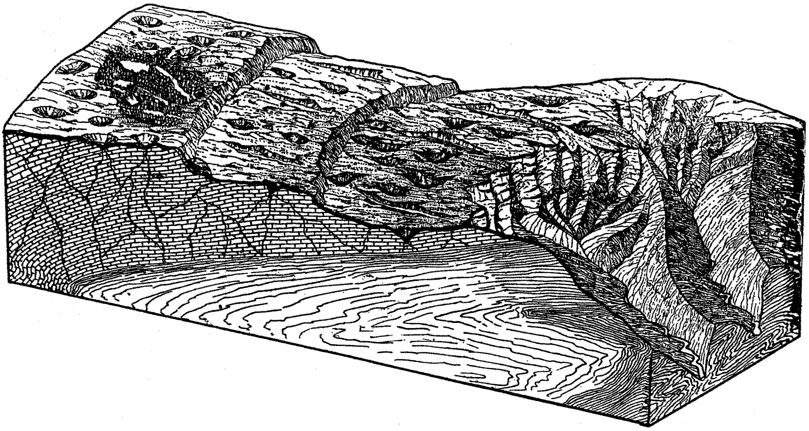

FIG. 9—A branch of the Narenta in Herzegovina, to illustrate regressive erosion in the karst, a special feature of the Dinaric lands where normal valleys in relatively insoluble rocks (right) are developed side by side with typical karst features (left) formed after an earlier period of normal erosion.

Examples of karst topography may be found in many parts of the United States. Among others, Tennessee, Kentucky, and Virginia have large areas where various stages of karst development may be seen.[8]

As the course of erosion proceeds, both the surface and the underground system are modified. The higher land separating the uvalas, or major depressions, is dissolved away, and many stretches of flat land are formed, surrounded by higher land which shows dolines and ponors (Fig. 6) and the irregular surface due to lapiez. The underground drainage is now fully developed, a network of caverns and channels permeating the entire mass of limestone. These channels are sufficient to carry off all the

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[8] For maps illustrating karst features in the United States, and for discussions thereof, see Salisbury and Atwood: The Interpretation of Topographic Maps, *U. S. Geol. Survey Professional Paper No. 60*, 1908, Pls. 90–94 and pp. 54–55.

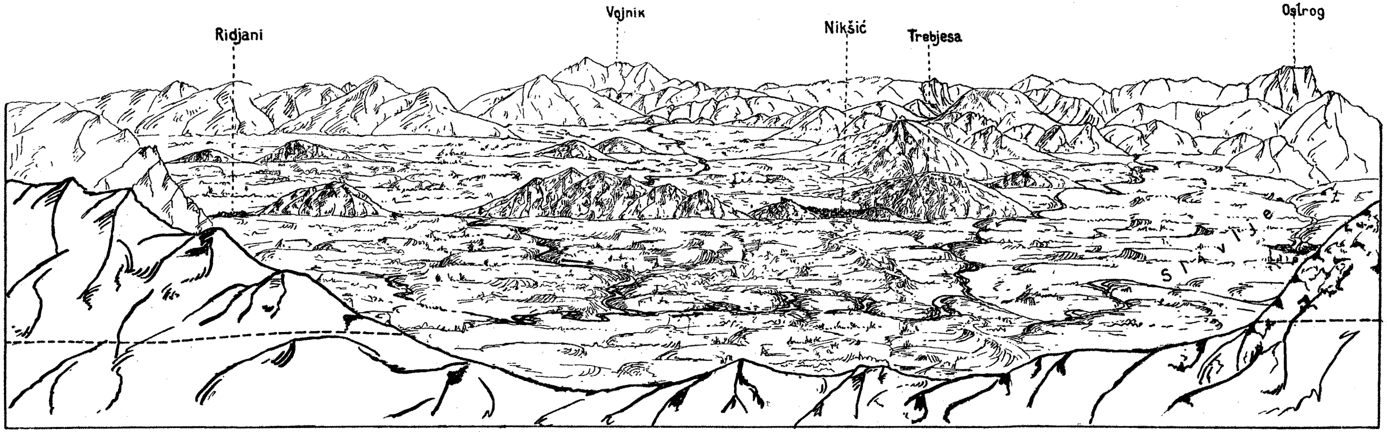

Fig. 10—General view of a polje strewn with hums. Polje of Niksic, Montenegro. Primarily of tectonic origin and now modified by stream action. Isolated hills are hums. The dashed line at left represents the course of the valley exit from the basin. Note the stream disappearing in a ponor at the extreme right.

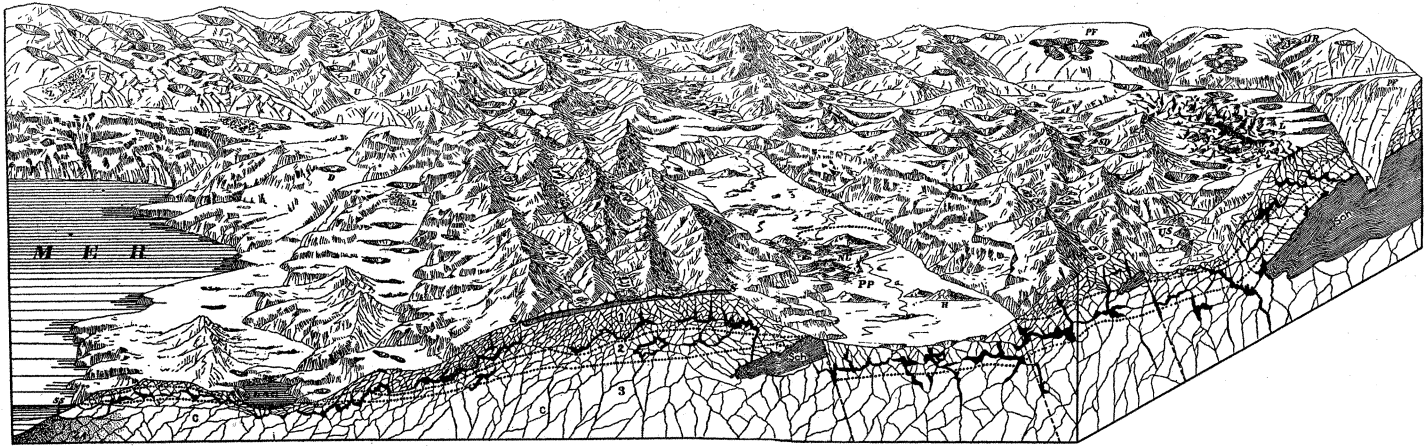

FIG. 11—Synthetic sketch of forms of the Dinaric karst. References to surface forms: L, lapiez; D, dolines; SD, uvalas formed by union of dolines; U, uvalas; US, uvalas uniting to form a polje; UR, uvala captured by regressive stream action; P, dry polje; PP, polje periodically flooded; LAC, polje lake; PF, peneplain remnants. Sch, schists; C, limestones; S-S, impermeable layer giving rise to local sources of water (springs and doline lake). References to underground drainage: 1, dry zone; 2, transition zone (intermittently wet and dry); 3, wet zone (constant circulation); ss, submarine springs and line of hydrostatic equilibrium; ZA, zone influenced by pressure of sea water.

water that falls as rain, and there are no permanent surface lakes. Terraces of alluvium surround the former lake basins. This stage is the maximum of karst development, its maturity. Figure 6 shows the sort of relief that is characteristic. Such topography is found developed to its greatest extent in the Dinaric coastal strip of the Adriatic Sea in Dalmatia.

The mature stage may be said to have passed the moment that any part of the underlying strata is laid bare. Now begins the decline, or the stage of late maturity, during which the limestone is gradually stripped off the underlying impermeable strata. Wherever this happens the drainage can no longer flow underground, and surface streams appear. At first they are not above ground for any long distance, occurring most frequently where the edge of the limestone mass is eaten away by regressive erosion as well as undermined by the extension of subterranean caverns. Figure 9 shows this development. The streams issue from a cavern; and, except near the edges of the limestone mass, they frequently flow into another cavern. Figure 8 shows one of these streams, with the remains of former caverns still standing as arches over the gorge in which the stream flows. This process goes on all over the karst region; cavern after cavern falls in, and gorges are created everywhere; the edges of the plateau suffering more than the interior, as is shown in Figure 9. The resulting topography is seen in Figure 6. The polje flow is again covered in part by an intermittent lake, and streams flowing in deep gorges exist side by side with dolines and uvalas.

Old age is reached by the continuance of the same process of unroofing of caverns and regressive erosion, which takes place both at the edges of the plateau and along the sides of the gorges where the streams cut back and capture the dolines and uvalas. Figure 6 shows the last stage: a normal system of surface streams is in possession of the land, the former limestone mass being represented by isolated fragments which Cvijić calls "hums." The French term for these outliers is "buttes temoines." The hums are mere shells honeycombed with caverns. Excellent examples of karst topography in its later stages may be seen in Natural Bridge County, Va., and in the causse of central France.